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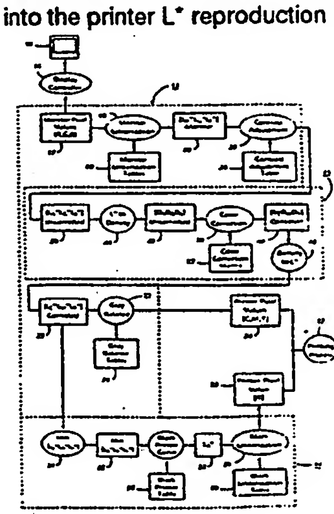
(54) Transforming colour monitor pixel values to colour printer pixel values

(57) An equivalent neutral L* (ENL*) transformation process is provided for transforming additive primary color [R,G,B] monitor pixel values that are supplied to display color images on a color monitor into subtractive primary color[C,M,Y], or subtractive primaries plus black [C,M,Y,K], printer pixel values for reproducing such images on a color printer. To carry out this process, a monitor/printer combination is linearized in L* of standard L*, a*, b* color space for neutral tones ranging from monitor black to monitor white for the monitor, and from printer black to printer white for the printer. Furthermore, the neutral-tone L* range of the monitor is translated into the neutral-tone L* range of the printer in accordance with a monotonic mapping function scaled to map monitor black to printer black, and monitor white to printer white. Monitor pixel values can then be transformed into printer pixel values, for example by serially reading their R, G, B terms and their C, M, Y or C, M, Y, K terms into and out of, respectively, look-up tables containing (1) appropriately-scaled and translated ENL* values indexed by the R, G and B terms of all possible monitor pixel values, and (2) the C, M and Y terms or the C, M, Y, K terms of all possible printer pixel values indexed by their ENL* values. A fixed monotonic mapping function may be employed for directly mapping the ENL* values of the R, G, and B terms of the monitor pixel values onto the C, M, Y or C, M, Y, K terms for the corresponding printer pixel values (using, for example a minimum L* criterion to select the ENL* value to be mapped onto the K term). Alternatively, an optional gray-balanced color-correction matrix may be employed to modify the manner in which the terms of the monitor pixel values map onto the terms for the printer pixel values, thereby permitting adjustments to be made to the color saturation and hue of the printed reproductions, without affecting their tone in L*. The tone of the printed reproductions scale in L* to the displayed images in accordance with the monotonic mapping function that is employed to translate and scale the monitor L* response range into the printer L* reproduction range and may, therefore, be adjusted by adjusting that function.

FIG. 1



GB 2213674 A

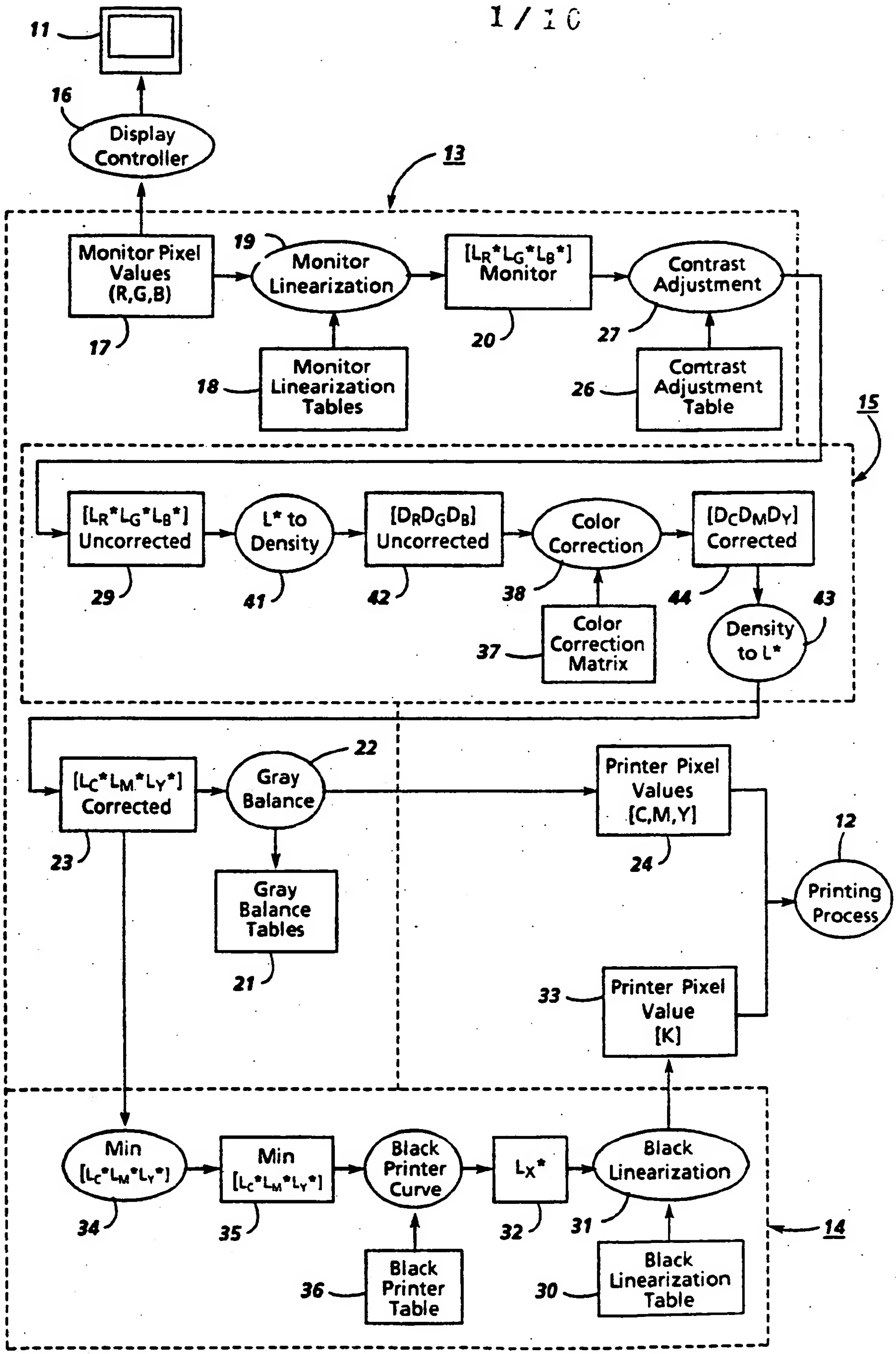
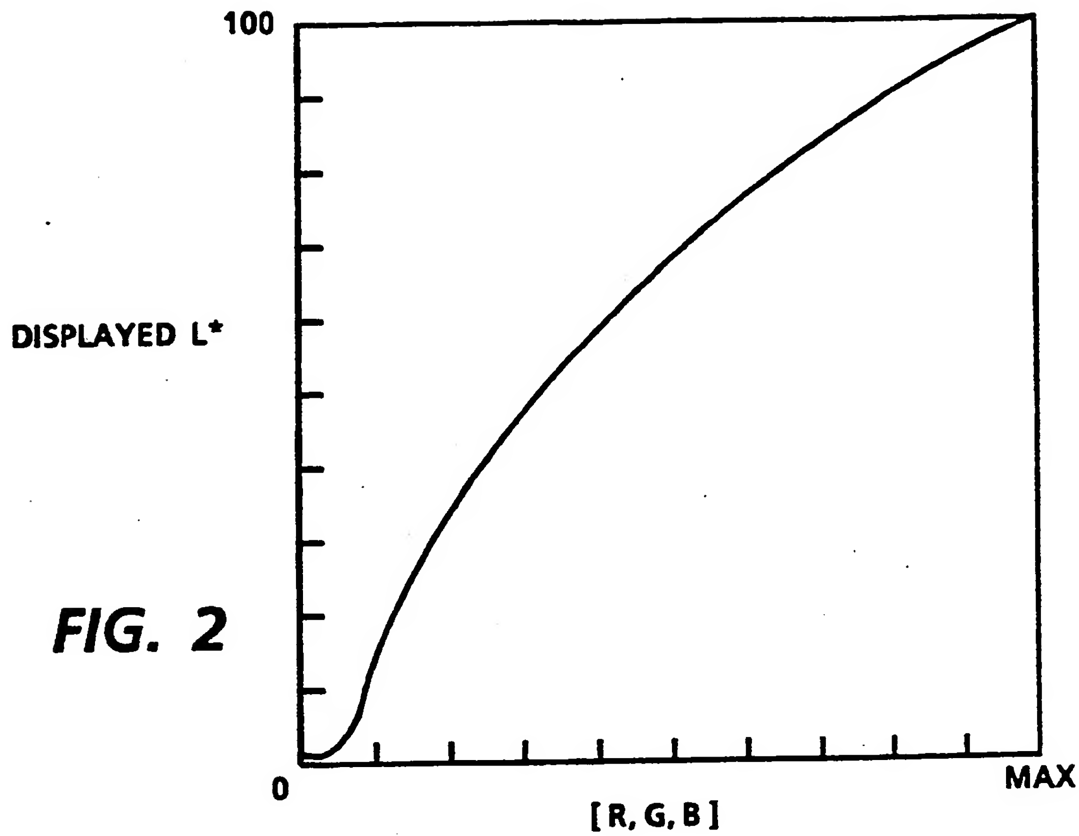
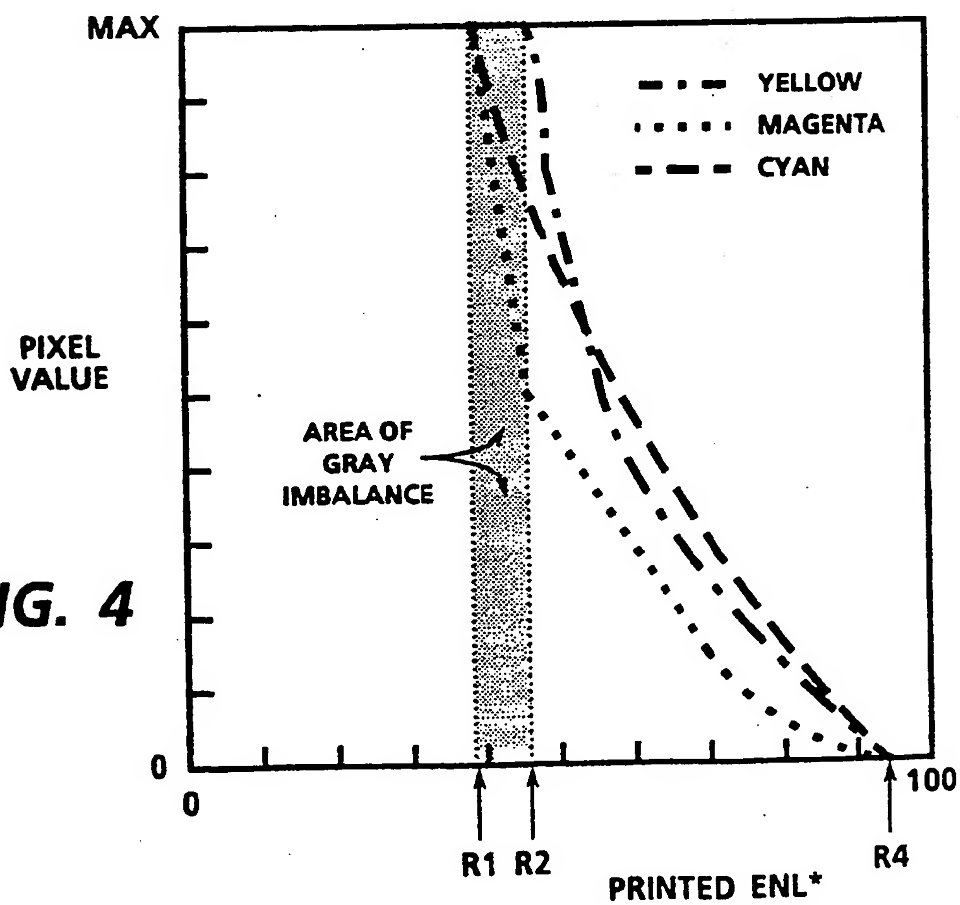

11
16
Display Controller
13
Monitor Pixel Values (R,G,B)
17
19
Monitor Linearization
18
Monitor Linearization Tables
[LR*LG*LB*] Monitor
20
Contrast Adjustment
27
26
Contrast Adjustment Table
15
[LR*LG*LB*] Uncorrected
29
L* to Density
41
[DRDGDB] Uncorrected
42
Color Correction
38
37
Color Correction Matrix
[DCDMDY] Corrected
44
43
Density to L*
[LC*LM*LY*] Corrected
23
Gray Balance
22
Gray Balance Tables
21
Printer Pixel Values [C,M,Y]
24
12
Printing Process
33
Printer Pixel Value [K]
Min [LC*LM*LY*]
34
Min [LC*LM*LY*]
35
Black Printer Curve
36
Black Printer Table
LX*
32
Black Linearization
31
30
Black Linearization Table
14

FIG. 1



100
DISPLAYED L*
0
MAX
[R, G, B]

FIG. 2



MAX
YELLOW
MAGENTA
CYAN
PIXEL VALUE
AREA OF GRAY IMBALANCE
0
0
100
R1
R2
R4
PRINTED ENL*

FIG. 4

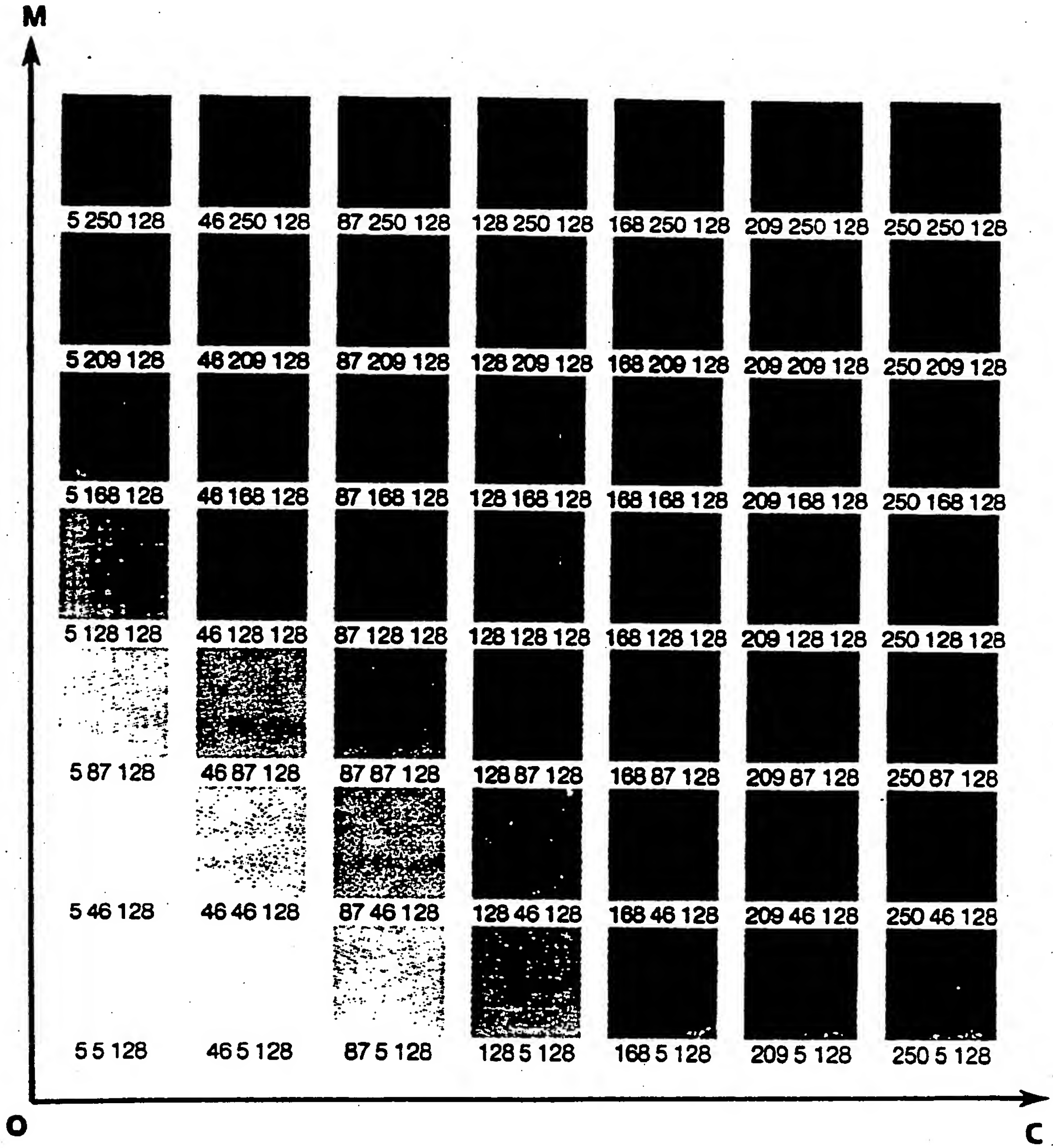

M
5 250 128
46 250 128
87 250 128
128 250 128
168 250 128
209 250 128
250 250 128
5 209 128
46 209 128
87 209 128
128 209 128
168 209 128
209 209 128
250 209 128
5 168 128
46 168 128
87 168 128
128 168 128
168 168 128
209 168 128
250 168 128
5 128 128
46 128 128
87 128 128
128 128 128
168 128 128
209 128 128
250 128 128
5 87 128
46 87 128
87 87 128
128 87 128
168 87 128
209 87 128
250 87 128
5 46 128
46 46 128
87 46 128
128 46 128
168 46 128
209 46 128
250 46 128
5 5 128
46 5 128
87 5 128
128 5 128
168 5 128
209 5 128
250 5 128
O
C

FIG. 3

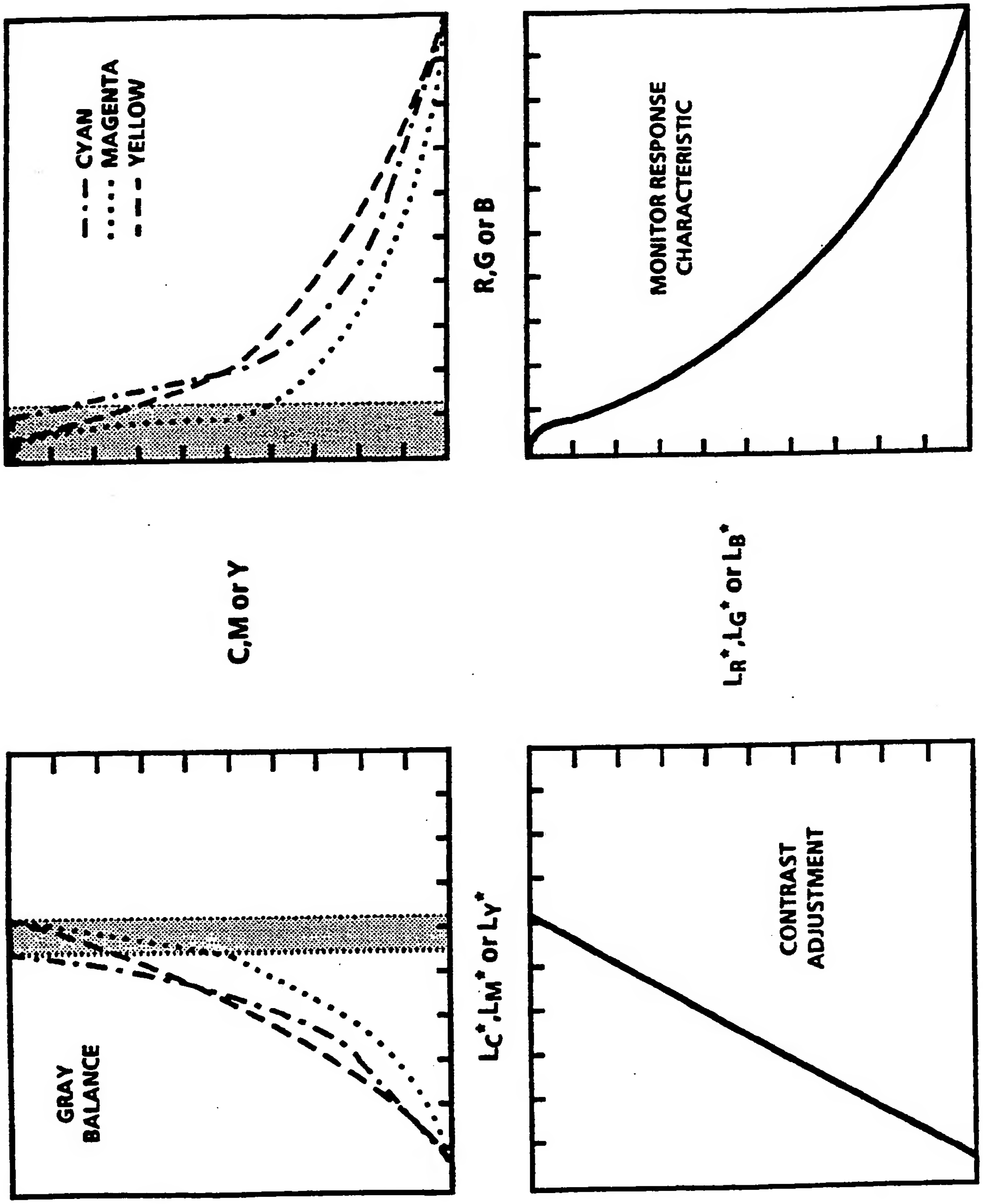

CYAN
MAGENTA
YELLOW
R,G or B
MONITOR RESPONSE CHARACTERISTIC
C,M or Y
L_R^*, L_G^* or L_B^*
GRAY BALANCE
L_C^*, L_M^* or L_Y^*
CONTRAST ADJUSTMENT

FIG. 5

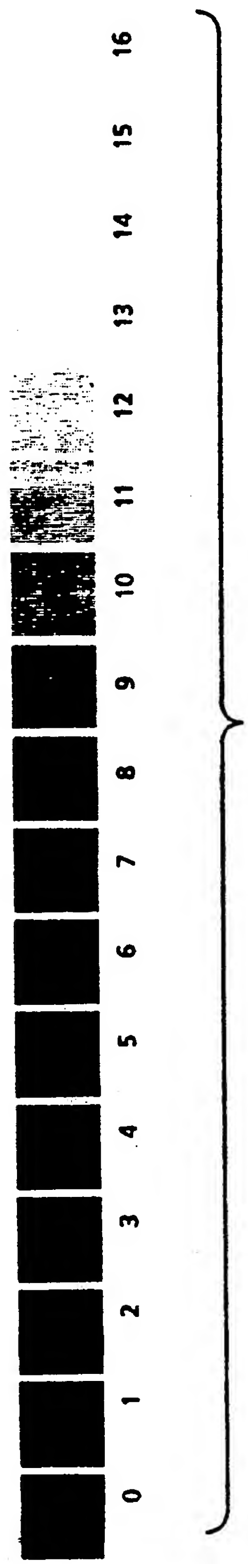


FIG. 6

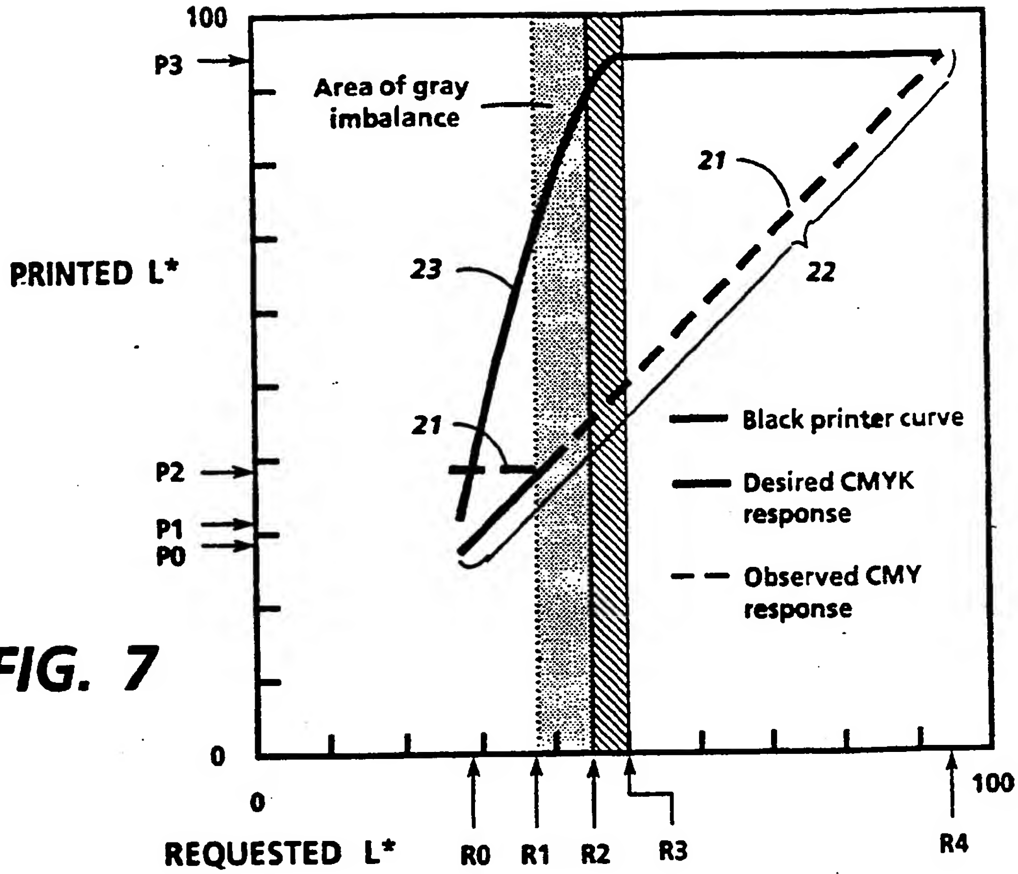

100
P3
P2
P1
P0
0
PRINTED L*
Area of gray imbalance
21
22
23
21
Black printer curve
Desired CMYK response
Observed CMY response
0
100
REQUESTED L*
R0
R1
R2
R3
R4

FIG. 7

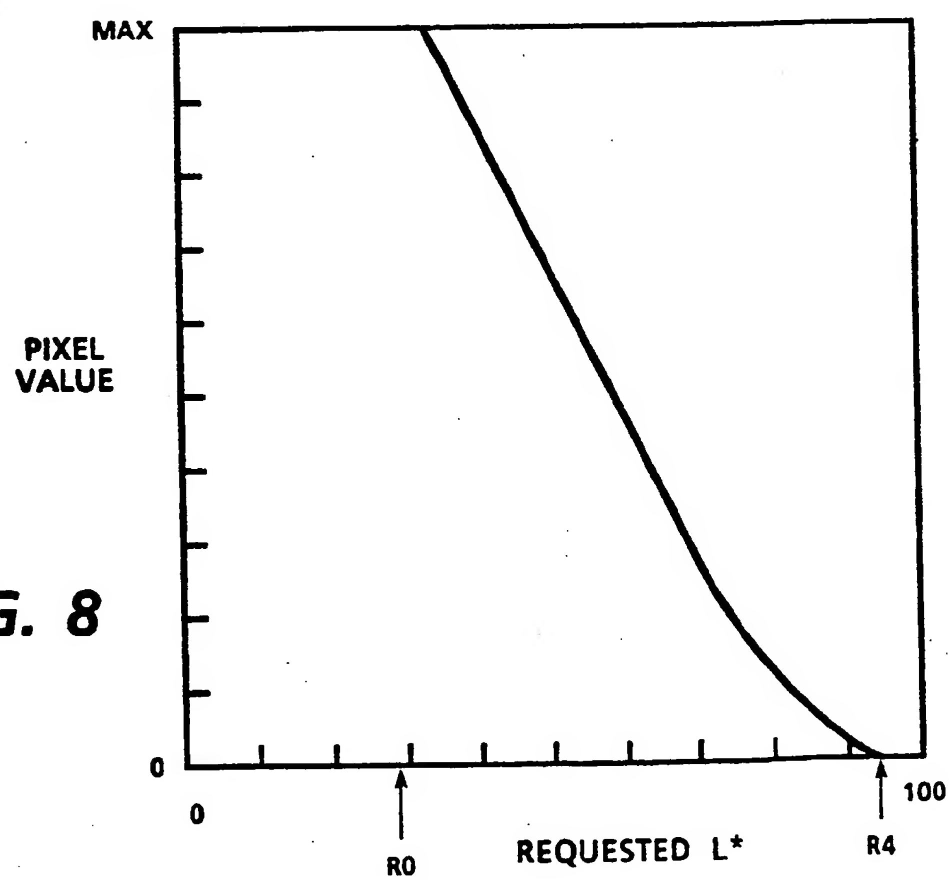

MAX
PIXEL VALUE
0
0
100
R0
REQUESTED L*
R4

FIG. 8

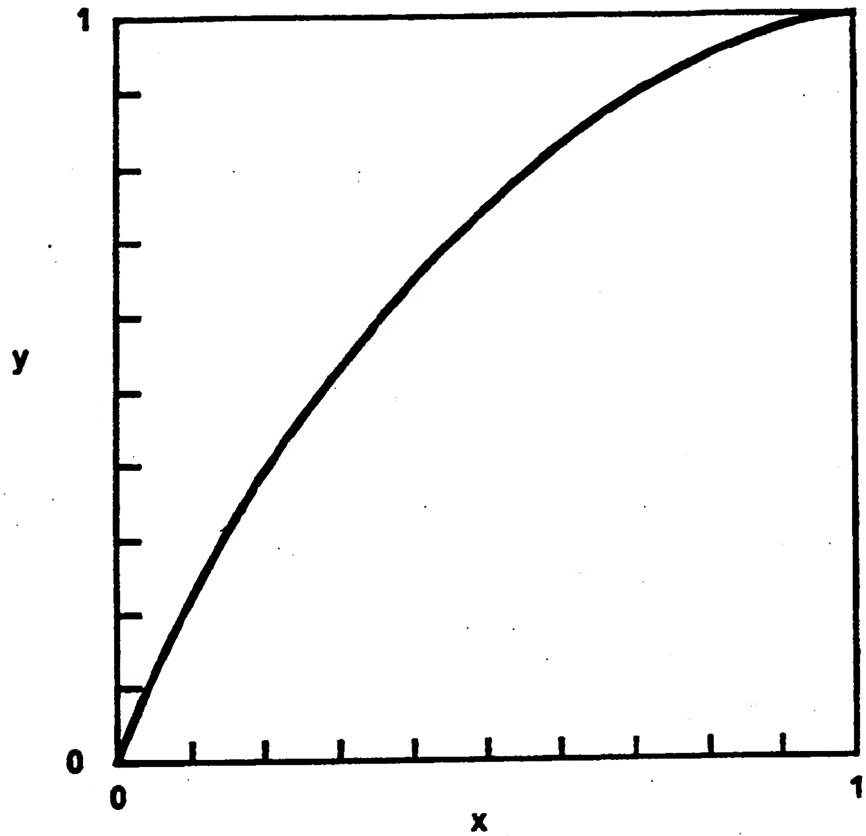

1
y
0
0
x
1

FIG. 9

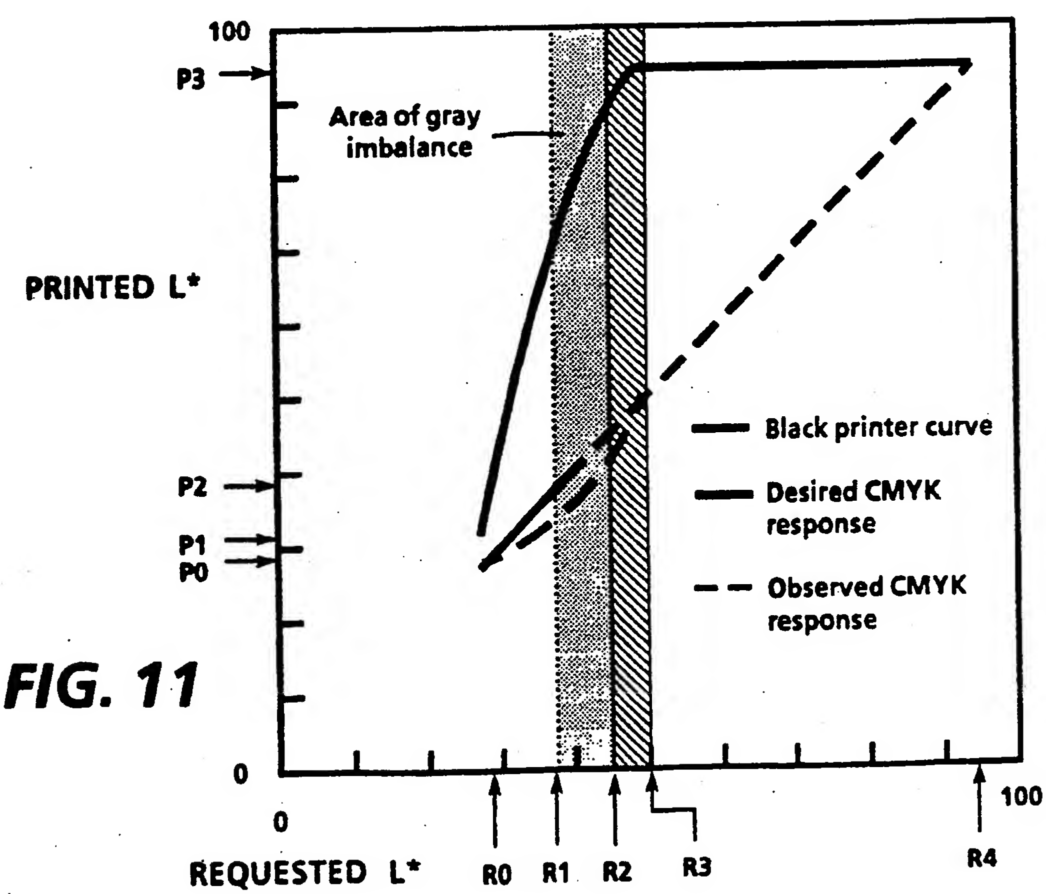

100
P3
Area of gray imbalance
PRINTED L*
P2
P1
P0
0
0
REQUESTED L*
R0
R1
R2
R3
R4
100
Black printer curve
Desired CMYK response
Observed CMYK response

FIG. 11

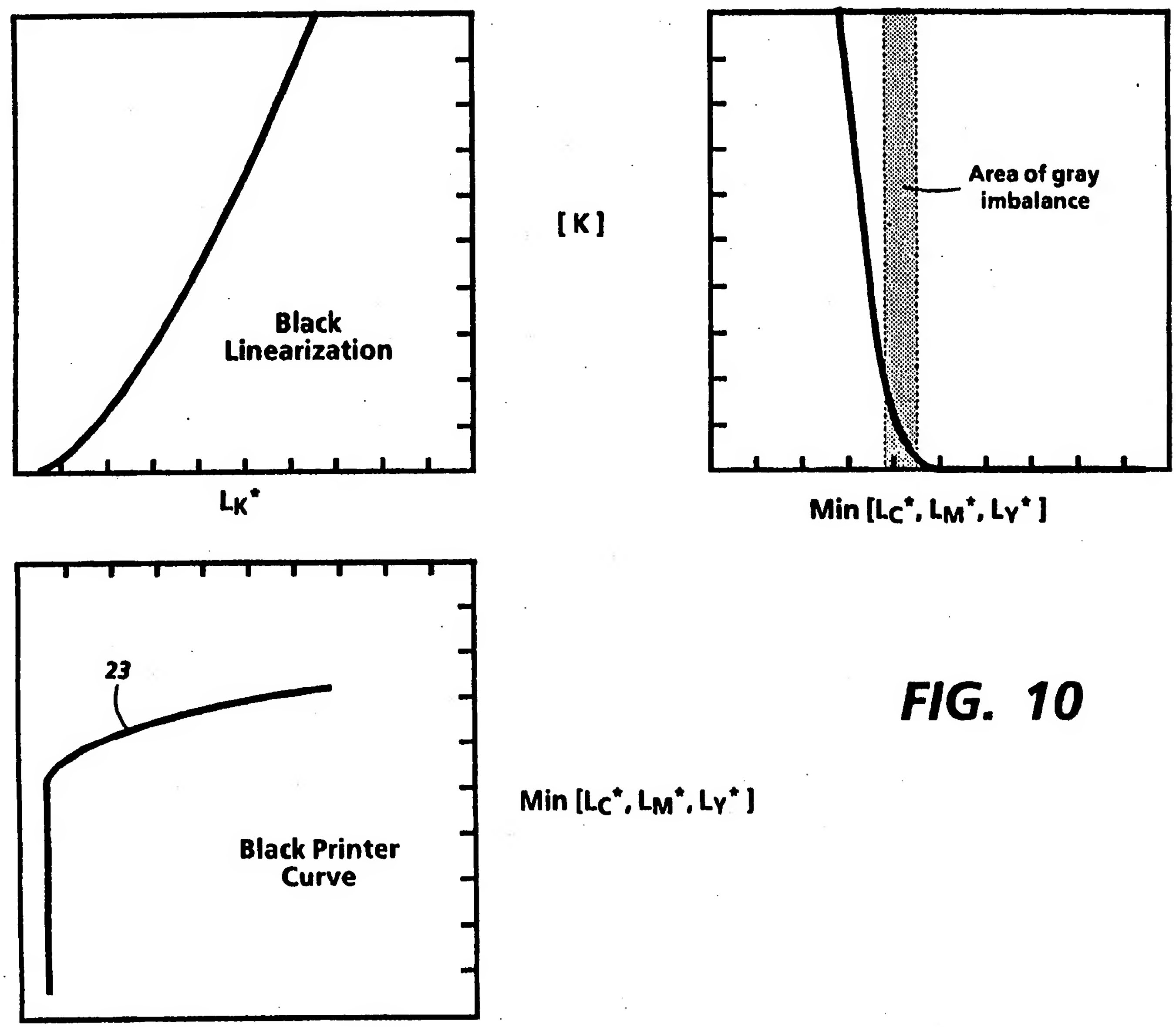

Black Linearization
L_K^*
[K]
Area of gray imbalance
Min $[L_C^*, L_M^*, L_Y^*]$
23
Black Printer Curve
Min $[L_C^*, L_M^*, L_Y^*]$

FIG. 10

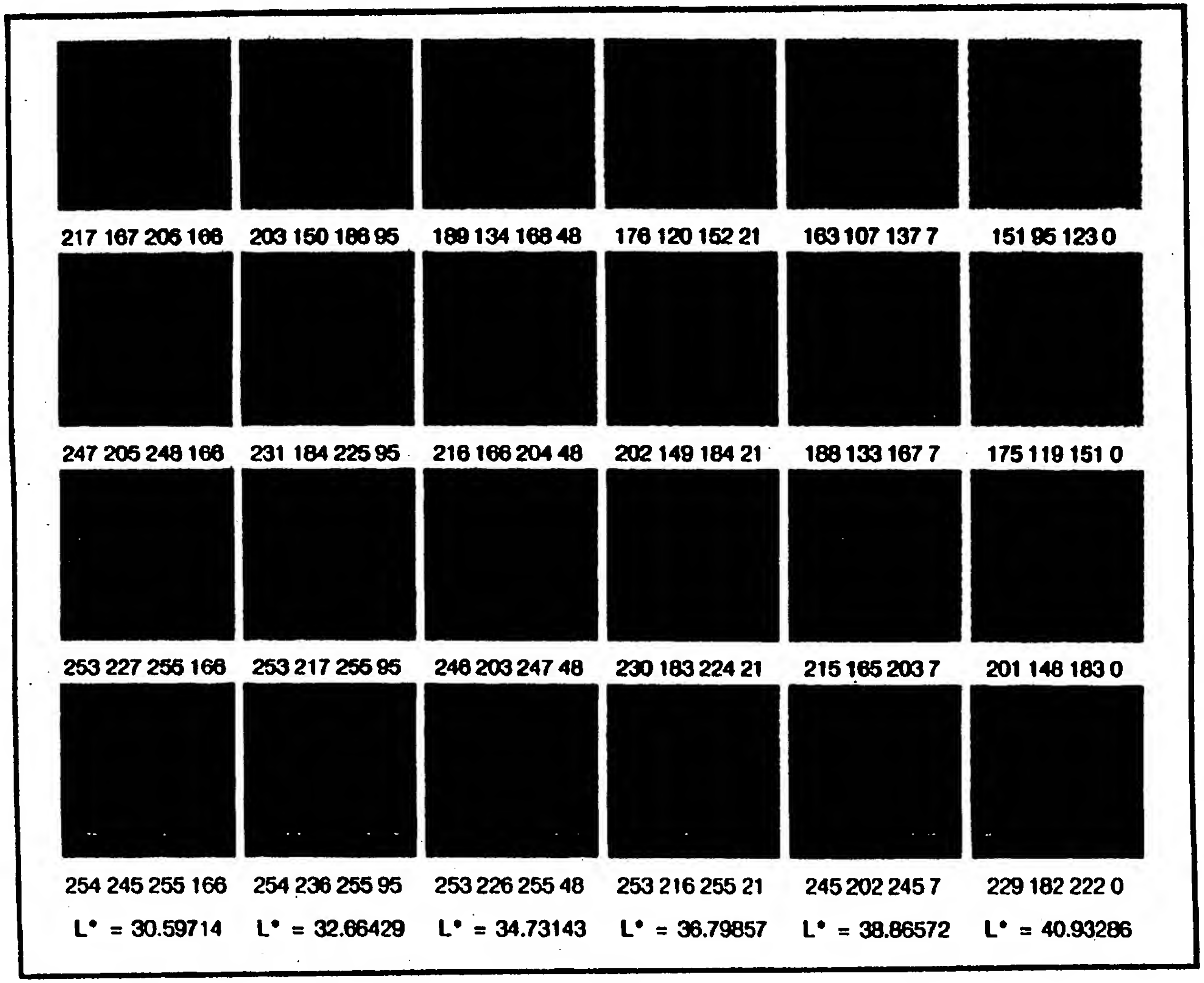

217 167 206 166
203 150 186 95
189 134 168 48
176 120 152 21
163 107 137 7
151 95 123 0
247 205 248 166
231 184 225 95
216 166 204 48
202 149 184 21
188 133 167 7
175 119 151 0
253 227 255 166
253 217 255 95
246 203 247 48
230 183 224 21
215 165 203 7
201 148 183 0
254 245 255 166
254 236 255 95
253 226 255 48
253 216 255 21
245 202 245 7
229 182 222 0
L* = 30.59714
L* = 32.66429
L* = 34.73143
L* = 36.79857
L* = 38.86572
L* = 40.93286

FIG. 12

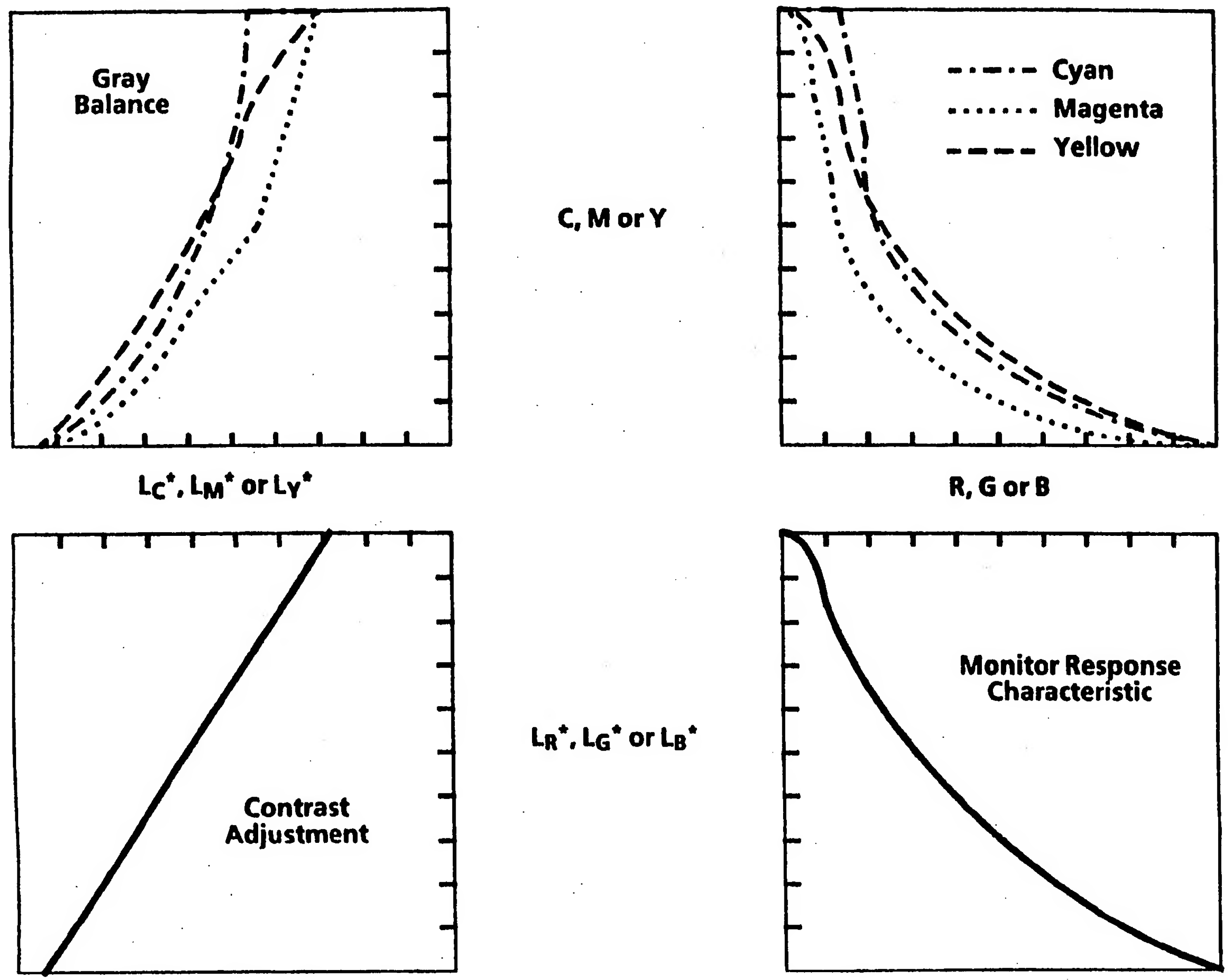

Gray Balance
C, M or Y
Cyan
Magenta
Yellow
L_C^*, L_M^* or L_Y^*
R, G or B
Contrast Adjustment
L_R^*, L_G^* or L_B^*
Monitor Response Characteristic

FIG. 13

This invention relates to the printing of computer generated color images and, more particularly, to a method for improving the printed appearance of such images.

Modern personal computer systems frequently are equipped with color monitors and color printers so that users can view and print color images. However, users of these systems often are disappointed by the poor color reproduction exhibited by the printed images, especially when careful consideration has been given to the coloration of the displayed image. Even though it is known that the data generated for the monitor should be transformed into a form suitable for the printer, most users of personal computer systems are ill-equipped to produce a satisfactory transformation because they are not skilled in color reproduction and do not have easy access to sophisticated color measuring equipment. Indeed, it is believed that many of these users are prepared to accept printed color images of less than full graphics art quality in exchange for a straightforward process that enables them to print color images that perceptually approximate the displayed images.

Others have proposed monitor data to printer data transforms based on colormetric matching and scaling of displayed and printed images on the theory that colormetric consistency leads to acceptable reproduction of computer generated color images. See, for example, W. F. Schrieber, "A Color Prepress System Using Appearance Variables," Journ. of Imaging Technology, Vol. 17, No. 4, August 1986, pp. 200-210 and M. C. Stone et al., "A Description of the Color Reproduction Methods used for this Issue of Color Research and Application." Color Research and Application, Vol. 11, Supplement 1986, pp. 583-588. Unfortunately, even if the instrumentation is available to make colormetric measurements, the look-up tables needed to implement such a transformation tend not only to be very large, but also to be very tedious and time consuming to construct, because a large number of printed samples usually have to be measured to produce a reasonably comprehensive set of printer data values. Moreover, colormetric matching usually requires that provision be made to deal with the ordinary differences between the color gamuts of the monitor and printer, such as by restricting the monitor color gamut to ensure that the printer color gamut is coextensive with it, or by uniformly compressing the monitor color gamut by a scaling factor selcted to fit it within the printer color gamut. Generally, such a gamut reduction sacrifices color saturation in various ranges of the spectrum, so the images produced frequently are disappointing.

Gordon et al., "On the Rendition of Unprintable Colors," Proceeding of the Technical Association of Graphic Arts, 1987, proposes an interesting alternative involving the uniform scaling of the monitor and printer gamuts in L*, u*. v* color space. However, such a scaling causes the brightness, hue and color saturation of the reproduced images to be mutually-dependent variables.

Thus, it is believed that a simpler and more flexible monitor data to printer data transformation process is needed to enable users of computer systems, especially personal computer systems, to obtain the printer data required for printing subjectively-acceptable color reproductions of computer-generated images.

In accordance with the present invention, there is an equivalent neutral L* transformation process for transforming the [R,G,B] monitor pixel values that are supplied to display color images on a color monitor into gray-balanced [C,M,Y] or [C,M,Y,K] printer pixel values for reproducing such images on a color printer. To carry out this process, a monitor/printer combination is linearized in L* of standard L*, a*, b* color space for neutral tones to identify equivalent neutral L*'s (ENL*'s) for the individual terms of the monitor and printer pixel values for all pixel values ranging from monitor black to monitor white for the monitor, and from printer black to printer white for the printer. Furthermore, the neutral L* range of the monitor is translated into the neutral tone L* range of the printer in accordance with a monotonic mapping function scaled to map monitor black to printer black, and monitor white to printer white. Monitor pixel values can then be transformed into printer pixel values, for example, by serially reading their R, G, B terms and their C, M, Y or C, M, Y, K terms into and out of, respectively, look-up tables containing (1) appropriately-scaled and translated ENL* values indexed by the R, G and B terms of all possible monitor pixel values, and (2) the C, M and Y terms (or the C, M, Y, K terms) of all possible printer pixel values indexed by their ENL* values. A fixed monotonic mapping function may be employed for directly mapping the ENL* values of the R, G, and B terms of the monitor pixel values onto the C, M, Y or C, M, Y, K terms for the corresponding printer pixel values (using, for example a minimum L* criterion to select the ENL* value to be mapped onto the K term). Alternatively, an optional gray-balanced color-correction matrix may be employed to modify the manner in which the terms of the monitor pixel values map onto the terms for the printer pixel values, thereby permitting adjustments to be made to the color saturation and hue of the printed reproductions, without affecting their tone in L*. The tone of the printed reproductions scale in L* to the displayed images in accordance with the monotonic mapping function that is employed to translate and scale the monitor L* range into the printer L* range and may, therefore, be adjusted by adjusting that function.

Other features and advantages of this invention will become apparent when the following detailed description is read in conjunction with the accompanying drawings, in which:

Figure 1 is a flow chart illustrating the monitor data to printer data transformation process of the present invention, including an optional black printer transform and an optional color-correction process;

Figure 2 is a L* linearization curve for a typical monitor;

Figure 3 is a black and white representation of a typical three-color test chart;

Figure 4 illustrates three-color ENL* gray-balance curves for a typical printer;

Figure 5 is a Jones chart concatenation of the curves shown in Figs. 2 and 4 with a monitor/printer specific contrast adjustment curve;

Figure 6 is a black and white representation of a three-color gray wedge of test patches which are substantially uniformly spaced in L*;

Figure 7 is a graphical representation of the correlation between the requested and printed L* values of three-color C,M,Y and four-color C,M,Y,K prints;

Figure 8 is a black printer L* linearization curve for the typical printer;

Figure 9 is a generic black printer curve;

Figure 10 is concatenation of the printer characteristic curve of Fig. 8 with the black printer curve of Fig. 7 to provide a printer gray-balance curve for the black component of a four-color (C,M,Y,K) print;

Figure 11 illustrates the effect of a black printer on the correlation function of Fig. 7, when only the C, M and Y color components are gray-balanced;

Figure 12 is a black and white representation of a typical four-color test chart such as may be used for adjusting the three-color C, M and Y gray-balance curves for four-color printing, and

Figure 13 is a Jones chart concatenation of the monitor response characteristic curve of Fig. 2 with the printer gray-balance curves and the monitor/printer contrast adjustment curve as modified for four-color (C,M,Y,K) printing.

At the outset it will be helpful to briefly define some of the terminology that is used herein and to identify the instrumentation that is recommended for use in calibrating the transformation process of this invention.

I. Terminology

As is known, color can be described with three variables. Red, green and blue light emitted by a CRT monitor or contained by the light emitted by a source and reflected from an object determines the characteristic of the light reaching the eyes. This is called the "stimulus." Three variables usually are sufficient to define a color stimulus. A perceptual color space set of variables (L*, a*, b*) has been established by the International Commission on Illumination, CIE. It was selected because its three variables correlate better than other standard specifications with the response of the human visual system to the stimulus. See G. Wyszecki et al, Color Science Concepts and Methods, Quantative Data and Formulae, Second Edition, John Wiley and Sons, New York, 1982, pp. 162-169.

The response which the stimulus evokes can also be described with three variables, such as hue, lightness and saturation. The lightness dimension depends on the relative

amount of light coming from an object or image. White objects have high lightness, while black objects have little or no lightness. L* closely correlates with lightness, and is usually assigned the vertical axis in three dimensional representations. Bright colors such as orange have high saturation and grays have zero saturation. Hue is associated with color names like purple, yellow and green.

For purposes of the following discussion, a pixel is defined as the smallest area of the monitor or print which can be independently colored. The transformation from monitor pixel values to printer pixel values determines the amounts of ink required to reproduce each red, green, blue (R, G, B) triad displayed on the monitor, and it is specific to a particular monitor/printer pair. Unfortunately there is no simple relationship between the pixel values driving the red, green and blue phosphors of a CRT monitor and the pixel values that are needed to produce an acceptable print. The inks corresponding with the red, green and blue additive primaries of the CRT are the subtractive primaries - cyan (red absorber), magenta (green absorber) and yellow (blue absorber).

As will be seen, the values used herein for the optional color and saturation correction are expressed in terms of density. Red, green and blue densities of the monitor are D_R, D_G and D_B, and the cyan, magenta and yellow densities are D_C, D_M and D_Y. Density is defined as $\log_{10} 1/r$, where r represents reflectance or, in other words, the ratio of the amount of light reflected from an area to the amount reflected from a white surface or from an absolute diffuse reflector.

The color components of a pixel are described with three or more variables called the pixel components. The notation [C,M,Y,K] indicates the value of a printer pixel. [C,M,Y] is shorthand for [C,M,Y,0], with C, M, Y and K representing the amounts of cyan, magenta, yellow, and black colorant, respectively, that the printing system is requested to place on the page at a given pixel location. These pixel values range from 0 to max. - a transform independent value. For example, if each of the color components is defined by an eight-bit byte, they have integer values in the range 0 to 255. $C = M = Y = K = 0$ means that no colorant is to be applied, while $C = M = Y = K = max$ means that all colors are to be applied maximally. In the interval between 0 and max (e.g., 255), the printing system responds monotonically.

As is known, an Equivalent Neutral Density (END) concept is used in photography to define the amounts of dyes in images in terms of their visual effect. In three-color photography, the END of one of the colorants is the density which would be produced if amounts of the other two dyes are added in just sufficient amounts to produce a gray color. This concept is useful in analyzing the lightness reproduction characteristics of other reproduction processes, so it has been widely adapted for that purpose in the graphic arts. However, in the following description, the lightness reproduction characteristic is expressed on a perceptually linear L* scale, rather than on the logarithmic density scale. Consequently,

the concept of Equivalent Neutral L* (ENL*) is used instead of Equivalent Neutral Density. The shortened version that is used herein is L^*_R, L^*_G, L^*_B for monitor values. Thus, it is to be understood that L^*_R, L^*_G, and L^*_B are measures of the amount of red, green and blue light, respectively, emitted by the monitor CRT in terms of their perceived visual effects. Similarly, L^*_C, L^*_M, L^*_Y, L^*_K for the printer define the amounts of cyan, magenta, yellow and black inks, respectively, that are to be printed on the paper or other recording medium in terms of their perceived visual effects.

The notation [R,G,B] denotes a monitor pixel value and L^*_R, L^*_G, L^*_B the amounts of red, green and blue, respectively, that the display system is requested to deliver to the screen. Thus, a monitor pixel value [R,G,B] = [0,0,0] implies a very dark color close to black (i. e., "monitor black"), while a value [R,G,B] = [max,max,max] implies a color very close to white (i. e., "monitor white"). Conversely, the L^*_C, L^*_M, L^*_Y, and L^*_K values of a printed pixel decrease for increasing amounts of cyan, magenta, yellow and black ink, respectively, so a printer pixel value [C,M,Y,K] = [0,0,0,0] represents "printer black", and a value [C,M,Y,K] = [max,max,max,max] represents "printer white." As will become evident, the transformation process of this invention causes grays on the monitor to reproduce essentially as grays on the prints whenever the [R,G,B] monitor pixel values are equal to each other for all monitor pixel values [v,v,v] in the range $0 < v < \max$.

II. <u>Recommended Calibration Instrumentation</u>

There are many instruments available for measuring color stimuli. Devices for measuring and adjusting a CRT monitor range from simple visual devices for adjusting its color balance to sophisticated telespectroradiometers for measuring the spectral emission of its phosphors wavelength by wavelength. Spectrophotometers, colorimeters and densitometers are used to measure prints. Every instrument has a value, but this invention can be implemented using two instruments; one to measure the monitor and the other to measure the print. It is recommended that both instruments have spectral responses similar to normal human vision as prescribed by the CIE.

More particularly, the monitor typically is measured using a color balance meter. For example, a Minolta TV-COLOR ANALYZER TV-2150 may be employed for adjusting and maintaining the ratio of red, green and blue emissions of the usual CRT. Such a device is also capable of determining the luminosity at various levels of lightness. If no comparable instrument is available, it is possible to get improved results by using a monitor which is well calibrated and maintained. However, measuring increases the level of confidence and is valuable in troubleshooting.

The second instrument is a colorimeter, such as a Minolta CR231, for measuring the color and lightness of prints in order to calibrate the printing process. The light source, filter,

and photodetector combination of such an instrument are designed to correspond with CIE X,Y,Z, and some of them directly convert to L*,a*,b*. The colorimeter also may be used to measure print densities, even though a densitometer may be a more convenient tool for some tasks. Of the two types of densitometers (broad band and narrow band), the narrow band is preferred.

III. The Transformation Process and Its Calibration

Turning now to the drawings, and at this point especially to Fig. 1, it will be seen that the transformation process of the present invention involves a sequence of calibration procedures which are performed in order to cause the [R,G,B] pixel values that drive a particular monitor 11 to transform into the [C,M,Y] or [C,M,Y,K] pixel values that enable a particular printing process 12 to print a subjectively-acceptable reproduction of a computer-generated color image displayed on the monitor 11. The printing process 12 is printer-specific, so the terms 'printing process' and 'printer' are used herein interchangeably. The data processing for transforming the monitor [R,G.B] pixel values to the printer [C,M,Y] or [C,M,Y,K] pixel values is performed between the monitor 11 and the printer 12, such as in a host computer (not shown) in an ordinary personal computer system, or in a print server containing a user specific monitor linearization and contrast adjustment table (also not shown) in a distributed processing system. Thus, the transformation is specific to a particular monitor/printer combination.

Achieving and maintaining an acceptable print quality from the printing process 12 requires routine examination of the prints that it is producing. As is known, the color of prints is affected by the illumination under which they are viewed, so the light source and viewing conditions under which test and sample prints are examined should be chosen with care and remain essentially constant. Additionally, a file of test prints, which are printed while the printer 12 is known to be properly calibrated, should be preserved for comparison against subsequently printed samples. If any significant difference between these two sets of prints is found to exist, the system should be recalibrated. The color of each ink is measured while the system is being calibrated. It is also useful to measure intermediate levels of lightness from time-to-time to determine if the L* response of the printer 12 to one or more given pixel values has significantly shifted or not. If such a shift is detected, the system should be recalibrated. On a routine basis, however, it is generally sufficient to measure only the maximum densities of the inks so as to determine whether the printing process 12 produces a consistent density from day-to-day. Of course whenever a new ink batch is used, the color should be checked by measuring the maximum density of each ink with a colorimeter, so that the system can be recalibrated if there is a significant change in the densities of the inks being used.

In practice, the black produced by the maximum density of cyan, magenta and yellow colorants alone may not be dark enough for some prints, and may have an objectionable hue. The addition of a black ink, therefore, often produces an important improvement in the perceived quality of the printed image by providing a black with less hue and greater density. Fortunately, as described in more detail hereinbelow, the amount of black to be printed can be directly derived from the three-color [C,M,Y] representation by making the amount of black a function of the minimum of any given triad of requested L^*_c, L^*_m and L^*_y values.

The transformation process involves three basic stages, the last two of which are optional; (1) a gray-balance and contrast adjustment stage 13 for establishing a desired black-to-black and white-to-white, monotonic correlation between the L* values of grays on the monitor 11 and those of the image printed by the printer 12, while ensuring that areas without hue (white, gray and black) on the monitor image are reproduced without any significant hue on the print, (2) a black printer stage 14 for incorporating a black image to supplement the three color image (this requires recalibration of the gray-balance and contrast adjustment stage 13 for four-color printing), and (3) a color-correction stage 15 for adjusting the hue and saturation of the printed image independently of its tone so that the non-gray areas of the image may be caused to correspond more closely with the monitor image, without affecting the tonal reproduction characteristics established by the gray-balance and contrast adjustment stage 13.

A. Gray-balance and Contrast Adjustment

1. Monitor Calibration - Deriving Monitor Linearization Tables

To detemine the L* response of the monitor 11 for all monitor pixel values [R,G,B], where R = G = B so that $L^*_R = L^*_G = L^*_B$, the monitor is first adjusted to its maximum contrast consistent with good performance. Preferably, both brightness and contrast are adjusted to predetermined levels every time the monitor 11 is used. Furthermore, the monitor 11 should be turned on and allowed to stabilize before it is used or any measurements are taken. It is assumed that equal [R,G,B] values for a given pixel will cause the monitor 11 to produce neutral white, gray or black at any lightness. However, It is extremely difficult to sense changes in monitor color visually, so instrumentation is used to calibrate the monitor 11 and to keep it constant. Typically, the monitor 11 is controlled by a display controller 16 in response to the [R,G,B] pixel values received from a frame buffer 17 or the like.

It sometimes is difficult to obtain reliably-repeatable measurements from inexpensive color monitors. The L* of a supposedly constant gray can change considerably over time, so all measurements preferably are taken within a short period. Moreover, all measurements are taken in the same area of the monitor screen, because on some monitors

differences as large as 60% have been measured between the center of the screen and its edges. Unfortunately, a constant gray will yield a different L* value if white is displayed on the monitor 11 shortly before the constant gray. Therefore, at least 10 to 20 seconds should be allowed for the monitor 11 to settle after each gray level change. Of course, the settling time may be reduced if all the changes in gray level are small.

L* measurements of the monitor 11 suitably are begun after it has been set to black [0,0,0] and allowed to settle. The L^*_{min} (monitor black) value is recorded at this setting; and the monitor 11 is then incremented in about 20 neutral tone steps to L^*_{max} (monitor white), with an L* measurement being taken at each step after the display has stabilized. Sufficient data are obtained to plot a curve, such as shown in Fig. 2, describing the monitor L* as a function of the monitor [R,G,B] pixel values for all neutral tones between monitor black and monitor white. This curve, called the monitor linearization curve, is subsequently used to find the particular printer pixel value combinations [C,M,Y] or [C,M,Y,K] which produce equivalent neutral tones on the printer as described hereinbelow. If the luminosity, *Y*, of the monitor 11 is measured instead of its L*, the maximum value of luminance, Y_W, is used to calculate the L* values using the following equation:

$$L^* = 116 \sqrt[3]{Y/Y_W} - 16 \tag{1}$$

The symbol *Y* is used for luminosity, rather than the standard CIE symbol, Y, simply to avoid ambiguity.

Given the monitor linearization curve of Fig. 2, a look-up table 18 (Fig. 1) of L* values, identically indexed by R, G, and B monitor pixel values, can be constructed to translate, as at 19, any R, G or B value supplied by the frame buffer 17 into a corresponding L^*_R, L^*_G or L^*_B value, respectively, as at 20.

2. <u>Printer Calibration - Deriving Interim Gray-balance Tables</u>

Step one in calibrating the printer 12 is to set its three-color zero saturation axis to have linear L* values and to be gray. For this operation, the optional black printer stage 14 is turned off. A series of test charts with varying amounts of cyan, magenta and yellow is printed in a sufficient number of combinations to obtain a series of nearly neutral tone patches with a range of L* values. Figure 3 illustrates one of these charts, with the label under each three-color patch identifying, from left to right, the C, M and Y pixel values applied to the printer 12. In this chart, cyan increases in value C from left to right and magenta increases in value M from bottom to top. Yellow has the same value Y over the entire chart, but varies from chart-to-chart. Enough charts are printed to obtain 8 to 10 substantially neutral tone patches having approximately equally spaced L* values between printer black and printer white. Then, as

shown in Fig. 4, so-called printer gray-balance curves are produced by plotting the [C,M,Y] pixel values of these neutral color patches against their L* values.

Colorimeter gray is defined as a* and b* equal to the white of the recording medium. Thus, to simplify the task of defining the ENL* gray-balance curves of the printer 11, it is helpful to set the colorimeter to read a* = b* = 0 when measuring the recording medium (e.g., paper). This makes it easier to identify grays. A patch that measures within approximately one unit of the defined gray point is found on each test chart (Fig. 3). If the test chart color steps are too coarse to provide such a patch, the [C,M,Y] pixel values of gray may be determined by interpolation. Indeed, additional near-gray color patches may have to be printed to define some grays with the desired precision. Initial printer gray-balance look-up tables 21 (Fig. 1) for translating, as at 22, requested [L^*_C, L^*_M, L^*_Y] values 23 into printer [C,M,Y] pixel values 24 can be derived from these three-color gray-balance curves, but these look-up values are subject to being amended if the optional black printer stage 14 is incorporated into the transformation process.

Considering Fig. 4 in some additional detail, it will be apparent that these three-color printer gray-balance curves define the relative amounts of the cyan magenta and yellow colorants that are needed to produce a neutral tone having a given L* value. However, it may not be possible to maintain tonal neutrality in the darkest prints if one of the colorants reaches a maximum before the others, as in the case of the yellow colorant in this particular example. This region of the printer ENL* axis (the gray-shaded portion between R1 and R2 in Fig. 4) is known as the area of gray imbalance. Handling the extension of the gray-balance curves for the two colors that are not fully exhausted at R2 is arbitrary and a matter of preference, so in this case both of those curves have been extended with a straight line from the last point at which a neutral tone can be produced, R2, to the minimum (darkest) L* request, R1, the printer 12 is required to honor. The L* value of the paper, R4, is the maximum value that can be requested.

If the maximum attainable 3-color neutral tone is sufficiently dark, the next two steps will complete the calibration procedure. Otherwise, however, these steps can be deferred until after the black printer stage 14 has been added.

3. Contrast Adjustment - Deriving Interim Contrast Adjustment Tables

Before any test pictures are printed, the monitor L* linerization function (Fig. 2) is combined with the printer L* gray-balanced linearization function (Fig. 4) to provide a direct mapping from R, G, and B monitor pixel values to C, M and Y printer pixel values, respectively. It is unlikely that the minimum and maximum neutral tone L* values of the monitor 11 will match those of the printer 12, so an additional translate and scale step is employed to map the monitor L* range monotonically into the printer L* range. The mapping function must be

properly scaled to map monitor white and monitor black to printer white and printer black, respectively, but the user may adjust the manner in which this function varies in L* to adjust the tonal reproduction characteristics of the printing process 12. Hereinafter it is assumed a tone reproduction that is linear in L* is desired, but it should be emphasized that the present invention provides sufficient flexibility to enable the user to select and change the tone reproduction characteristic of the printing process 12 as needed to satisfy any special requirements or personal tastes.

A properly-scaled linear function for mapping the L* range of the monitor 11 into the L* range of the printer 12 is easily determined, as illustrated in the lower left quadrant of Fig. 5, by first finding the intersections of monitor white L* with printer white L*, and of monitor black L* with printer black L* when those values are projected from identically-scaled, orthogonal L* axes and by then joining those two intersection points with a straight line to define a contrast adjustment curve as shown. Although a linear contrast adjustment curve is not essential for carrying out this invention, it is useful to determine at least the intersection points that are needed to construct one as described above, because those end points of the curve must remain fixed to map monitor white and black onto printer white and black, respectively.

Given the desired contrast adjustment curve, a look-up table 26 (Fig. 1) can be constructed for translating the monitor L^*_R, L^*_G and L^*_B values 20 into L* requests as at 23 and 29 that are re-scaled into the L* range of the printing process. As will be seen, these re-scaled L* requests are expressed in terms of printer requests L^*_C, L^*_M and L^*_Y values, respectively at 23, but continue to be expressed in terms of L^*_R, L^*_G and L^*_B at 29 because they may differ from the L^*_C, L^*_M and L^*_Y values, respectively, at 23 if the optional color-correction stage 15 is utilized. However, it is to be understood that even if the color-correction stage 15 is utilized the look-up table 18 provides the appropriate L* values for directly translating monitor L^*_R, L^*_G and L^*_B values into the L^*_C, L^*_M and L^*_Y, respectively, that are required to cause the printing process 12 to reproduce any neutral tone. In other words, the tone reproduction characteristics of the printing process 12 are independent of any color-correction provided by the color-correction stage 15.

4. <u>Summary</u>

To summarize the foregoing, Fig. 5 shows how the transform of the present invention can combine the monitor L* response (Fig. 2), the monitor/printer contrast adjustment curve (lower left quadrant), and the printer gray-balance curves (Fig. 4) to produce a single mapping from monitor [R,G,B] pixel values to printer [C,M,Y] pixel values. The result, shown in the upper right quadrant of Fig. 5, is plotted by traversing the other three quadrants in clockwise direction starting at the [R,G,B] axis and ending at the [C,M,Y] axis. Each red (R),

green (G), and blue (B) term of a given [R,G,B] monitor pixel value is fed through the monitor L* response characteristic (bottom right quadrant) to obtain its ENL* value. This L* value is then monotonically mapped and scaled into the printer ENL* range using the contrast adjustment curve (bottom left quadrant). That, in turn, permits the printer ENL* value for a R, G or B term to be transformed into its complementary cyan (C), magenta (M) or yellow (Y) term using the appropriate gray-balance curve (upper left quadrant), thereby transforming the given additive primary color [R,G,B] monitor pixel value into a subtractive primary color [C,M,Y] printer pixel value that scales to the monitor pixel value in L*. The curves shown in the upper right-hand quadrant of Fig. 5 are a concatenation of the curves shown in the other three quadrants, so it will be evident that the monitor linearization look-up table 18, the contrast adjustment look-up table 26, and the gray-balance tables 21 of Fig. 1 can be combined to quantize the monitor response curve, the contrast adjustment curve and the gray-balance curves in as few as three look-up tables; one each for C, M and Y as indexed by R, G and B, respectively.

5. <u>System Verification for Desired Tone Scaling</u>

Referring again to Fig. 1, to verify that the monitor linearization provided by the look-up table 18, the contrast adjustment provided by the look-up table 26, and the printer gray-balance provided by the look-up table 21 cause the tone reproduction of the printer 12 to scale, for example, substantially linearly in L* to the tone of images displayed on the monitor 11, a test chart (Fig. 7) containing several neutral 3-color patches, which are substantially uniformly spaced in L*, are displayed on the monitor 11 and printed by the printer 12. Suitably, the monitor L* response (Fig. 2) is used to determine the [R,G,B] pixel values that will generate these 3-color patches at the desired L* spacing. As will be appreciated, the system should be recalibrated if the patches on the printed version of the test chart are not essentially gray and substantially uniformly spaced in L*.

After the tone reproduction of the three-color transform has been satisfactorilly adjusted, it is recommended that a few color images be printed. There is likely to be more apparent detail in these prints than in prints made directly from monitor data, but they may not yet be subjectively satisfactory reproductions of the displayed images.. Their most obvious defect is likely to be a lack of color saturation.

B. <u>Stage II - Incorporation of the Optional Black Printer Transform</u>

1. <u>Overview</u>

However, a significant improvement to the appearance of the printed images may be realized merely by incorporating the optional black printer stage 14. There are various algorithms for transforming [C,M,Y] printer pixel values into [C,M,Y,K] values, where K is the

term identifying the amount of black ink that is to be overprinted on the C, M and Y color separations, and for adjusting the [C,M,Y] values to compensate for the additional density provided by the black ink. Care should, however, be exercised in determining the maximum amount of black, K_{max}, that will be printed. For example, the transfer properties of the printing process 11 may limit the total amount of colorant that can be deposited in any given area. Ink jet printers are a case in point, because an excessive amount of liquid ink is likely to cause unwanted soaking of the paper. Likewise, prints produced by some thermal transfer printing processes may suffer reduced density as a result of overprinting them with black at certain gray levels.

J. A. C. Yule, Principles of Color Reproduction, John Wiley and Sons, New York, 1967, pp. 2-87, proposes an algorithm that accomplishes the twin goals of forcing the "area of gray imbalance" to be gray and of increasing the maximum density of the printing process 12. Fig. 7 illustrates a Yule function for the black printer transformation process 14 (Fig. 1), with the function being adapted to describe the effect of printing black on the perceptual lightness, L*, of the print. More particularly, in Fig. 7, the line segments 21 illustrates how L* requests are satisfied by the representative printer 12 using cyan, magenta and yellow colorant alone. With such 3-color printing, all L* requests below R_1, the point at which the printing process 11 reaches C_{max}, M_{max} or Y_{max}, produce the same output response, P_2. The desired response is, however, an identity function, as represented by the line 22. Thus, the curve 23 represents the amount of L^*_K that has to be printed in addition to the L^*_C, L^*_M and L^*_Y values to satisfy the desired identity function 22. In practice, the black printer curve 23 is allowed to extend slightly beyond the gray imbalance area R_1-R_2, so that it includes an overlap zone, R_2-R_3. This overlap reduces the slope of the black printer curve 23 when black is first introduced into the printing process 12, thereby ensuring that sufficient black is available to compensate for the gray imbalance R_1-R_2 of the printing process 12, while making the point at which black is first introduced into the process less noticeable.

As will be appreciated, the incorporation of the black printer stage 14 requires recalibration of the above described ENL* monitor data to printer data transform because the addition of black tends to extend the L* contrast range of the printing process 12 and to alter its gray-balance. Thus, the look-up values in both the contrast adjustment table 26 and the gray-balance tables 21 need to be adjusted to account for the affect of the black printer stage 14 if it is used.

2. Amending the Contrast Table

To determine the value, K, of the maximum amount of black ink that should be printed, a series of patches with value [C_{max}, M_{max}, Y_{max}, K], for 0<[K]<maximum available pixel value is overprinted with different amounts of black ink. The L* value of these 4-color

patches should decrease monotonically as K increases. If this condition is met for all values of K, then the K_{max} term is set to the maximum available pixel value. If, on the other hand, there is a serious departure from a monotonic response, a patch printed using less black is found from which all other patches decrease monotonically in L* for $0<K<K_{max}$, thereby identifying K_{max} from the patch of pixel value $[C_{max}, M_{max}, Y_{max}, K_{max}]$ that is found. In either case, P0 can be measured directly from the patch $[C_{max}, M_{max}, Y_{max}, K_{max}]$. That patch represents the darkest gray the printing process 12 is able to produce, so R0 = P0 is the darkest gray that may be requested of the printer and, therefore, becomes " printer black." Also, a patch [0,0,0,Kmax] is printed and its L* is measured to determine P1, which is the L* value of the maximum amount of K ever to be printed. Now the contrast adjustment table 26 can be recomputed using R0 and R4 as the upper and lower limits, respectively, of the L* contrast of the printing process 12.

3. Determining the Black Printer Linearization Table

To determine the L* response of the printer 12 to the printing of black, a range of patches is printed with black ink only, and their black L* values versus black printer pixel values are plotted to define a black printer L* characteristic curve, such as shown in Fig. 8. This curve, in turn, may be quantized to construct a look-up table 30 (Fig.1) for translating, as at 31, black L^*_K, requests 32 into their corresponding black pixel values 33.

4. A Recommended Black Printer Table

The black printer curve 23 of Fig. 7 was directly derived from Yule's aforementioned teachings by mapping data from Yule's black printer curve into L* space, fitting a polynomial to that data, and then scaling the curve defined by the polynomial to fit a unit square. As shown in Fig. 9, that procedure created a generic black printer curve that can be scaled to match the requirements of a particular printer. The polynomial function that describes the particular generic black printer curve shown is $y = 4.5x^3 - 1.84x^2 + 2.39x$.

To produce the black printer curve 23 of Fig. 7, the generic black printer curve of Fig. 9, as bounded by the unit rectangle [0 , 0], [1 , 1], was linearly scaled to fit a rectangle with bottom-left and top-right corners at [R0, P1] and [R3, P3], respectively, in Fig. 7. The curve then was completed by extending it horizontally with a straight line at level P3 (L* of the paper) as far as R4, thereby ensuring that all L* requests greater than R3 (the L* at which black is introduced) would call for the printing of no black color component.

5. The Operation of the Black Printer Stage

Fig. 10 is a concatenation of the black printer curve 23 of Fig. 7 with the characteristic L* response of the printer 12 to the printing of black, so it illustrates how the

gray-balance curve for black, K, is determined. Suitably, the minimum of the triad of requested [L^*_c, L^*_m, L^*_y] values for the printing of a given pixel is determined at 34 (Fig. 1) and set equal to the requested L^*_K for that particular pixel as at 35. As shown in Fig. 1, the black printer curve 23 (Fig. 7) may be quantized to reduce it to a look-up table 36 of printed values of L^*_K, as at 33, indexed by such requested L_k^* values 32 to translate the requested L^*_K values into the appropriate L^*_K values 32 for the printing process 12. As will be seen, those printer required L^*_K values 32 are, in turn, mapped through the black printer linearization table 30 to determine, as at 32, the value 33 for the black term, K, of the four-color [C,M,Y,K] printer pixel value.

6. Amending the Gray-balance Tables

At this point, the gray-balance curves for each of the four C, M, Y and K colorants can be used to produce grays throughout the newly-extended density range. Unfortunately, however, the combination of the four gray-balance curves can no longer be expected to provide a predictable response in L*. As shown in Fig. 11, the problem is that the addition of the black colorant often drives the four-color response of the printing process 12 below its desired straight line response 22 (Fig. 7) in the proximity of the gray imbalance area R1-R2 (it must drive the L* response of the printing process at least to this level to compensate for the colorant deficiency in its gray-imbalance area). For that reason, the C, M and Y gray-balance curves for the printer process 12 may have to be adjusted to restore the four-color response of the printer to it straight line target 22 (Fig. 7).

To determine the modified shapes for the C, M and Y gray-balance curves, a four-color test chart, such as shown in Fig. 12, may be printed based on the existing C, M and Y gray-balance curves. Preferably, the patches on this test chart are more or less uniformly distributed in L* space, so that the C, M and Y gray-balance curves can be recomputed substantially as previously described to provide updated values for the gray-balance look-up tables 21 (Fig. 1) as required to account for the use of the black printer stage 14. Figure 13 is another Jones chart illustrating the transformation process as modified to include the black printer stage 14.

C. Stage III - Saturation Improvement and Color-correction

Returning again to Fig. 1, a simple 3 x 3 gray-balanced color-correction matrix 37 may be used in the optional color-correction stage to modify, as at 38, the mapping of non-neutral [R,G,B] monitor pixel values onto the [C,M,Y] or [C,M,Y,K] pixel values in order to adjust the color saturation and hues of the printed image if desired. The illustrated color-correction procedure assumes that its input and output are density vectors, so there are additional mapping steps for converting, as at 41, the contrast adjusted monitor ENL* values [L^*_R, L^*_G, L^*_B] that are found at 29, into density values [D_R, D_G, D_B] which appear at 42, and for

reconverting, as at 43, the color-corrected printer density values [D_c, D_m, D_y] appearing at 44 into color-corrected requested printer ENL* values [L^*_c, L^*_m, L^*_y] provided at 23. A convenient place to perform the L*-to-density and density-to-L* conversions 41 and 43 is after the contrast adjustment process 27, but before the printer gray balancing 22.

More particularly, the color-correction matrix 37 takes the general form:

$$D_c = a_{11}D_R + a_{12}D_G + a_{13}D_B$$
$$D_m = a_{21}D_R + a_{22}D_G + a_{23}D_B$$
$$D_y = a_{31}D_R + a_{32}D_B + a_{33}D_B$$

The coefficients a_{11}, a_{22}, and a_{33} are the main terms of this matrix, and the remaining coefficients are its side terms. The matrix 37 is gray-balanced because the coefficients for the cyan, magenta and yellow densities that it produces, D_c, D_m and D_y, each always sum to a unity value (i.e., $D_c = D_m = D_y = 1$). Of course, if the cyan, magenta and yellow inks were precise complements of red, green and blue, respectively, the color-correction matrix would be an identity matrix (i.e., its main terms a_{11}, a_{22}, and a_{33}, would each be equal to 1, and its side terms would each be equal to 0), and no color-correction would be needed or provided. Unfortunately, however, such a complementary relationship is unavailable using known inks.

Suitably, a trial-and-error procedure is used to adjust the color-correction matrix 37, thereby enabling the user to adjust the saturation and hue of prints to personal subjective tastes. Test prints are produced on the printer 12, suitably starting with a unity matrix or a matrix adjusted based on prior experience, and these prints then are compared against the corresponding images as displayed on the monitor 11. If desired, the overall color saturation of these prints can be increased by equally incrementing all of the main terms of the color-correction matrix by a small amount, while decrementing each of its side terms by half that amount. The reverse decreases the overall color saturation of the prints.

Saturation or desaturation of specific hues is accomplished by selectively changing the coefficients in one or two rows of the correction matrix. The following table summarizes the sense of the side term adjustments that provide correction for the six major hues:

	Too Red	Too Yellow	Too Green	Too Blue
Reds	N/A	-a(31)	N/A	+a(31)
Greens	N/A	-a(32)	N/A	+a(32)
Blues	-a(13)	N/A	+a(13)	N/A
Cyans	N/A	N/A	-a(31)	-a(21)
Magentas	-a(32)	N/A	N/A	-a(12)

Yellows	-a(23)	N/A	-a(13)	N/A

Again, however, the matrix coefficients should be adjusted to provide the best coloration for average pictures. They are likely to be modified a number of times before a final set is established. At best, however, it is likely to be found that this or any alternative color-correction technique that may be employed is a compromise at best, because it generally is possible to obtain brighter and more saturated colors on the monitor 11 than by the printing process 12. Moreover, it is unlikely that any one set of coefficients for the color-correction matrix 37 will be optimum for all images, so it is to be understood that it may be desirable to adjust the coefficients for unusual or especially-important images. By way of example only, the matrix coefficients that were found to be subjectively satisfactory for reproducing color images deemed to represent an "average image" adequately are:

1.2	-0.1	-0.1
-0.35	1.45	-0.1
-0.30	-0.35	1.65

These coefficients may be a useful starting point for determining the optimum matrix coefficients for other printing processes and other images.

If this optional color-correction procedure 15 is employed, all possible mappings from the monitor [R,G,B] pixel values to density can be pre-computed and stored in a look-up table indexed by the monitor pixel values. Furthermore, the matrix multiplication operations for a established set of matrix coefficients, and their mapping to color-corrected density $[D_C, D_M, D_Y]$ values or requested $[L^*_c, L^*_m, L^*_y]$ values, can be pre-computed and stored in a look-up table indexed by the scaled but uncorrected density values $[D_R, D_G, D_B]$. Thus, color-correction may be implemented by means of a few table-look up and addition operations.

CONCLUSION

In view of the foregoing, it will now be apparent that the present invention provides a relatively-simple and highly-flexible process for transforming monitor pixel values expressed in additive primary color terms [R,G,B] into printer pixel values expressed in subtractive primary color terms [C,M,Y], with or without the addition of a black printer term for four-color [C,M,Y,K] printing, and with or without color-correction of the color saturation and/or hue of the printed image reproductions. The transformation process is calibrated to the ENL* responses of a specific monitor/printer pair, so that the tone of the images reproduced by the given printing process scale in L* in accordance with a predetermined scaling function to the tone of the images displayed on the given monitor such as in accordance with a linear function. However, if this predictability is unnecessary, such in the case of an occasional user,

the transformation process might be employed with a monitor and/or printer for which it has not been calibrated. Furthermore, the user may modify the L* tone scaling of a particular monitor/printer pair by making only a few straightforward adjustments to the manner in which monitor ENL* values map onto printer ENL* values. The tone scaling is independent of the saturation and hue of the reproduced images, so users who elect to employ the optional color-correction process that has been proposed may do so without risk of upsetting the L* tone scaling of the transformation process.

Claims:

1. A method for transforming monitor pixel values, expressed in primary additive color terms for displaying color images on a color monitor, into printer pixel values, expressed in subtractive primary color terms for printing reproductions of the images on a color printer; comprising the steps of

characterizing the monitor in L* throughout a neutral-tone response range extending from monitor black to monitor white, thereby determining equivalent neutral L* values for the primary color terms of all of the monitor pixel values;

characterizing the printer in L* throughout a neutral-tone reproduction range extending from printer black to printer white, thereby determining equivalent neutral L* values for the subtractive color terms of all of the printer pixel values;

translating the characterized response range of the monitor into the characterized reproduction range of the printer, in accordance with a monotonic function scaled to map monitor black to printer black, and monitor white to printer white; and

indexing the subtractive primary color terms of the printer pixel values by the additive primary color terms of the monitor pixel values through the equivalent neutral L* values of the additive terms as mapped onto the equivalent neutral L* values of the subtractive terms, whereby the monitor pixel values are transformed into printer pixel values for printing image reproductions that are tone-scaled in L* to corresponding images as displayed on the monitor.

2. The process of Claim 1, wherein the primary additive color terms of the monitor pixel values are mapped onto cyan, magenta, and yellow terms for the printer pixel values for three-color printing.

3. The process of Claim 2, further including the step of color-correcting the ENL* values of the terms of non-neutral monitor pixel values to modify the mapping of them onto the terms of the printer pixel values, thereby adjusting the color saturation of at least some hues of the reproductions.

4. The process of Claim 1, wherein the primary additive color terms of the monitor pixel values are mapped onto cyan, magenta, yellow and black terms of the printer pixel values for four-color printing, using a predetermined criterion to select one of the additive color terms for mapping onto the black term.

5. The process of Claim 4, wherein a minimum equivalent neutral L* criterion is employed to select the primary additive color term to be mapped onto the black term.

6. The process of Claim 5, further including the step of color-correcting the ENL* values of the terms of non-neutral monitor pixel values to modify the mapping of them onto the cyan, magenta and yellow terms of the printer pixel values, thereby adjusting the color saturation of at least some hues of the reproductions.

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